Modelling the polarisation mode control of single quantum-dot emission in elliptical micro-pillar microcavities based on DBR mirror pairs using the FDTD method

Y. -L. D. Ho, T. Cao, P. S. Ivanov, M. J. Cryan, I. J. Craddock, C. J. Railton, and J. G. Rarity
Centre for Communications Research, Department of Electronic and Electrical Engineering, University of Bristol, Bristol, BS8 1UB, UK.
Daniel.Ho@bristol.ac.uk

Abstract: We use the finite difference time domain method (FDTD) to investigate polarisation control of single-photon emission from single quantum dots confined in elliptical micro-pillar microcavities. In contrast to circular pillars, one of the cavity modes has smaller modal volume and maintains high Q-factor.

OCIS codes: (230.3990) Microstructure devices; (270.5580) Quantum electrodynamics

1 Introduction

Recently, single photon source have been realised by coupling InAs quantum-dots into a circular micro-pillar microcavity based on distributed Bragg reflectors (DBRs) [1-3]. These sources can be highly efficient because the high semiconductor refractive index collects a large fraction of the spontaneous emission into the waveguide mode. For quantum information application, polarization mode control of single-photon sources is important to allow encoding in polarisation and to avoid birefringence in the optical components. Hence we consider polarisation control of single-photon emitters in pillar microcavities and study the electromagnetic field distribution by changing the cross-section from circular to elliptical [4]. We aim to design highly efficient single-photon polarisation operation for very large Purcell factors (F_p).

2 Geometries of circular and elliptical micro-pillar microcavities

We use the 3-D finite difference time domain (FDTD) method to analyze circular and elliptical micro-pillar microcavities based on DBR mirror pairs as shown in Fig. 1. The micro-pillar microcavity is designed to be made of III-V semiconductor materials (AlAs/GaAlAs) with quarter-wavelength-period stacks resonant at the wavelength of 980 nm for large radius [5]. Here we will concentrate on the results from elliptical pillar with a 1.5 µm major axis (z-polarisation) and a 0.5µm minor axis (x-polarisation) and on 0.6µm circular pillars. The pillars consist of a GaAs λ-cavity between a 27 pair AlGaAs/GaAs DBR lower mirror and a 20 DBR pair upper mirror.

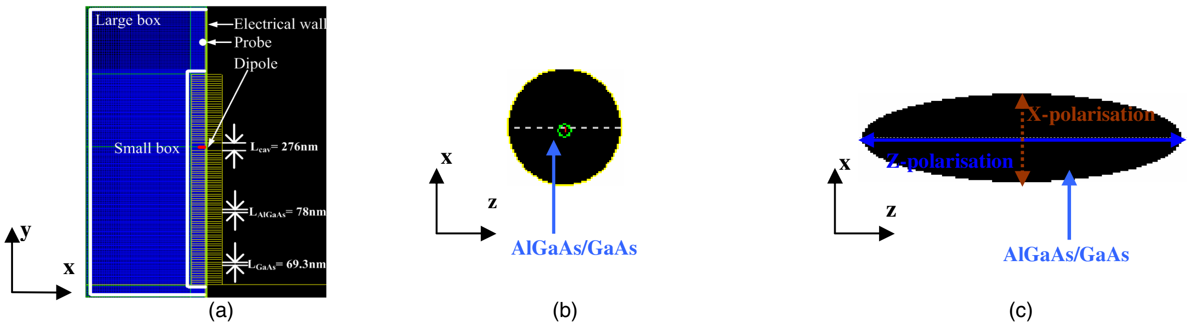

Fig. 1. (a) Y-X plane of device showing the mesh, electrical wall, probes, dipole, cavity thickness (L_{cav}), and DBR periodicity (L_{AlGaAs}, L_{GaAs}). (b),(c) are the top view of circular and elliptical pillar.(c) also illustrates the x-polarization (red dashed line) and z- polarization (blue solid line).

3 Simulation Results and Discussions

We place a broad band Ex-dipole source in the centre of the microcavity and input a short few-cycle excitation pulse to model the emission from the quantum dot. The cavity then rings at its resonant frequency and we monitor this using a probe above the pillar. Taking the Fourier transform of the ringdown signal (in time) allows us to determine the resonant frequencies of the of the cavity as shown in Fig. 2 (a) eand also to an estimate the Q-factor

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(Q=λ/Δλ). We then focus solely on the cavity resonant frequency to plot electric field distributions in figures 2(b-j), and estimate emission efficiency and enhancement into the cavity mode (the Purcell factor).

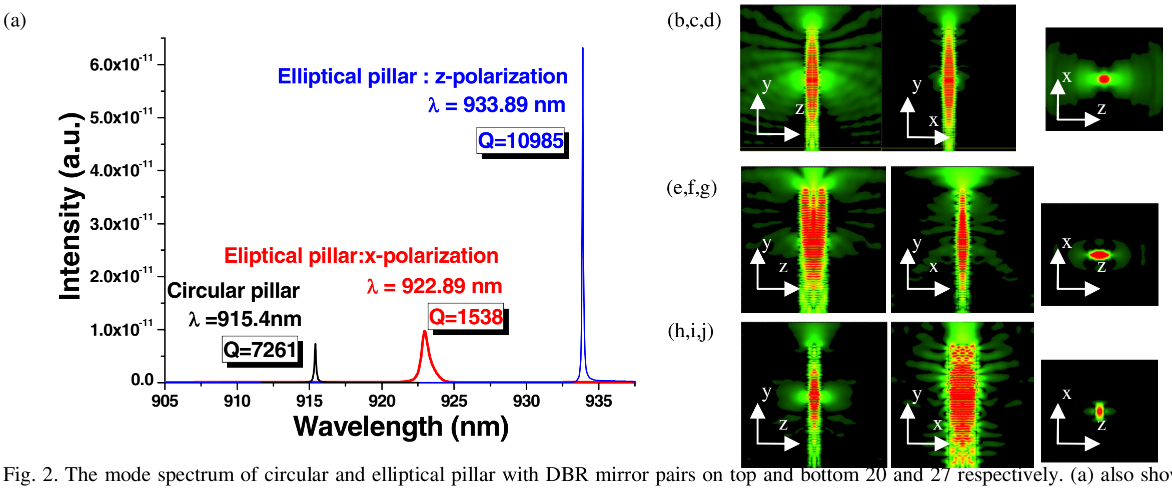

Fig. 2. The mode spectrum of circular and elliptical pillar with DBR mirror pairs on top and bottom 20 and 27 respectively. (a) also show the fundamental resonance of 915.4 nm with Q- factor of 7261, and 922.89 nm (x-polarised mode) with Q- factor of 1538, and 933.89 nm (z-polarised mode) with Q- factor of 10985. The measurements of the single frequency 'snapshot 'of (b), (c), (d) circular pillar microcavity, (e), (f), (g) x-polarization, and (h), (i), (j) z-polarization of elliptical pillar, for each plane are in the fundamental HE_{11} mode.

In the elliptical pillar we find two resonant modes corresponding to the x- and z-polarisation modes. The x-polarised mode is a low Q-factor mode due to lowered mirror reflectivity for this polarization. However the Q-factor of the z-polarized mode remains high despite the small cross-sectional area of the elliptical pillar. This suggests we can maintain high Q-factor with a low effective mode volume (V_{eff}) and thus achieve high Purcell factors. In these preliminary calculations we have seen Q-factor of 10985 in the z-polarised mode and 1538 in the x-polarised mode for elliptical pillar with a 1.5 µm major axis and a 0.5µm minor axis. Using the electric field distributions we can estimate V_{eff} = 0.07599 $_{\mu m}{}^3$ and thus predict a Purcell enhancement of F_p =204.97 for z-polarisation. In contrast, for the circular Pillar of radius 0.6 µm we see a mode volume V_{eff}= 0.03855 $_{\mu m}{}^3$ and predict a Purcell enhancement of F_p =251.52

4 Conclusions and Further Work

We show the progress toward the polarization mode control of single-photon sources in elliptical micro-pillar microcavities using 3-D FDTD method. We have seen our preliminary result for the Purcell factor of 204.97 in z-polarisation. In the future, we will continue the study of various structure shapes to aim for the smallest possible modal volume with high-Q operation. This will eventually bring us to the strong coupling regime of reversible spontaneous emission in which the cavity dynamics are described by vacuum-field Rabi oscillations [6,7].

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References

1. P. Michler, et al, "A Quantum Dot Single-Photon Turnstile Device," *Science* **290**, 2282 (2000).
2. J. M. Gérard, et al, "Quantum boxes as active probes for photonic microstructures: The pillar microcavity case," *Appl. Phys. Lett.* **66**, 449 (1996).
3. M. Pelton, et al, "Three-dimensionally confined modes in micropost microcavities: quality factors and Purcell factors," *IEEE J. of Quantum Electronics* **38**, 170 (2002).
4. A.J. Bennett, et al, "Polarization control of quantum dot single-photon sources via a dipole-dependent Purcell effect," *Phys. Rev. B* **72**, 033318 (2005).
5. Y.-L. D. Ho, et al, "Modelling quantum dots in micro-pillar micro-cavities for single-photon sources", International Quantum Electronics Conference, San Francisco, USA (2004).
6. J. P. Reithmaier, et al, "Strong coupling in a single quantum dot-semiconductor microcavity system," *Nature* **432**,197 (2004).
7. T. Yoshie, et al, "Vacuum Rabi splitting with a single quantum dot in a photonic crystal nanocavity," *Nature* **432**,200(2004).